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Partial Parallel Dual Active Bridge Converter with Variable Voltage Gain for SOEC/SOFC System

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Abstract— Fuel cells are becoming one of the promising devices in distributed generation (DG) systems due to their modularity, low or zero pollution and dispatchability. As one of the fuel cell technologies, solid oxide electrolysis cell / solid oxide fuel cell (SOEC/SOFC) has gained more and more attention owing to their relatively high efficiency. However, design of the interface system for SOEC/SOFC is challenging because of the current-dependent and low stack voltage, the slow cell dynamics and transient response, and the asymmetrical power characteristic of SOEC/SOFC. In this paper, a self-circulating modulation (SCM) is proposed for the partial parallel dual active bridge (P²DAB) converter. The SCM makes the voltage gain of the P²DAB converter variable, given the inherent high voltage gain characteristics of the topology itself, the P²DAB converter with SCM can thereby address the current-dependent and low stack voltage issues of SOEC/SOFC. Moreover, by using a SOFC-Parallel-SOEC-Series interface architecture, the asymmetrical power characteristics of SOEC/SOFC do not degrade the efficiency of the P²DAB converter. Finally, the analysis of the proposed SCM is verified on a 1MHz, 500W, 400V/50V, GaN-based P²DAB converter.

Keywords—Reversible fuel cells, power converter, dual active bridge, GaN

I. INTRODUCTION

Fuel cells are energy conversion devices that convert the chemical energy of fuel directly into electrical energy [1]. It is becoming one of the promising devices in distributed generation (DG) systems. Because fuel cells can be modularly implemented, fuel cell systems can be built in small size and then be placed close to electrical loads, enabling the thermal energy as a byproduct of the reaction to be used for cogeneration applications, making the combined efficiency attractive [2]. Due to its improved efficiency and low or no-carbon fuel sources, fuel cell systems typically generate low pollution. Besides, as a dispatchable DG unit, fuel cell systems are considered to be more reliable and more flexible in operation than non-dispatchable DG units such as wind or photovoltaic systems [3]. Furthermore, fuel cell systems can also be used to buffer the intermittent energy generated by renewable energy resources such as wind and solar to help ensure a high reliability of DG systems [4].

As one of the fuel cell technologies, solid oxide fuel cell (SOFC) produces electricity directly from oxidizing a fuel. If the same SOFC can also be used for electrolysis process, it is known as reversible SOFC, or combined solid oxide electrolysis cell / solid oxide fuel cell (SOEC/SOFC) [5]. The key feature of SOEC/SOFC systems is the high operating temperature, which is usually around 600-1000 Celsius degree. This high operating temperature simplifies the system configuration of SOFC by permitting internal reforming, facilitates the development of cogeneration systems [6] and

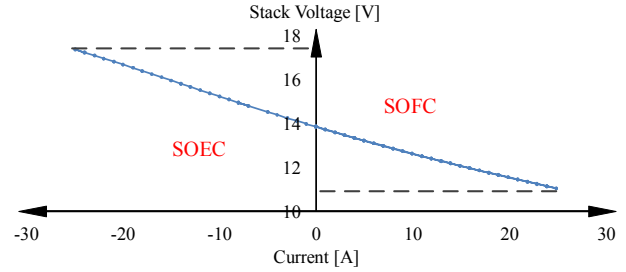


Fig. 1. Typical I-V curve of SOEC/SOFC

increases the electrical-to-chemical conversion efficiency of SOEC [7].

Bidirectional power electronics converters are the enabling technology facilitating the interface of SOEC/SOFC to the DG systems. Specifications of the converters need to be decided according to the characteristics of SOEC/SOFC. Fig. 1 shows the I-V curve of a SOEC/SOFC stack composed of 14 cells. Design of the bidirectional converters is challenging due to the current-dependent and low stack voltage [8], the slow cell dynamics and transient response [9], and the asymmetrical power characteristic of SOEC/SOFC [10].

A large number of converter topologies and control strategies have been proposed to address the current-dependent and low stack voltage issues of SOEC/SOFC. In [11], a full bridge dc/dc converter with a transformer composed by multiple windings was proposed for the interface of grid-tied SOFC. The windings on the high voltage side of the transformer can be separately disconnected, therefore, the converter has a variable voltage gain to ensure efficient operation over a wide input voltage, which is the stack voltage of the SOFC. In [12], instead of having multiple transformer windings in series on the high voltage side as proposed in [11], several full bridges were connected in parallel on the low voltage side. Through disabling some of the full bridges on the low voltage side, variable voltage gain was achieved to meet efficiency goals in the interfacing of SOFC. In [13], a two-stage conversion structure was applied for the application of SOEC/SOFC. A CLLC resonant converter was used to achieve high voltage gain, and an interleaved buck converter was employed control the output voltage, which is the voltage of the stacked cells. By implementing close-loop control to the above proposed converters, the slow cell dynamics and transient response issues can be addressed. However, addressing the SOEC/SOFC's asymmetrical power characteristics issue is challenging due to the symmetrical power characteristics of the power converters themselves [10]. In [10], a new architecture was proposed to deal with the asymmetrical power characteristics of SOEC/SOFC. Instead of connecting

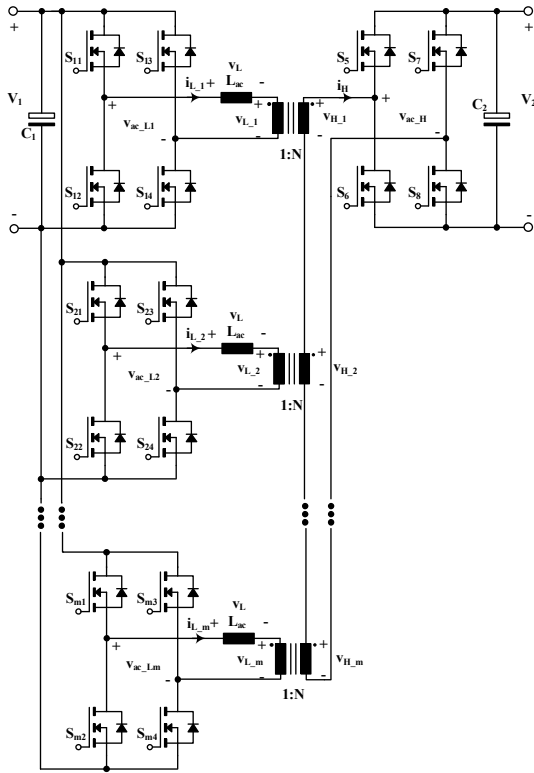


Fig. 2. Topology of the P²DAB converter

converters to stacks in parallel at both of the SOEC and SOFC modes, the converter is put in parallel to the stacks in SOFC mode, and in series to the stacks in SOEC mode. With this novel architecture, the operating power of the converters becomes much more symmetrical.

In [14], a partial parallel dual active bridge (P²DAB) converter was proposed. The P²DAB converter has high voltage gain which makes it potentially suitable for the interface of SOEC/SOFC to the grid. In this paper, in order to address the current-dependent stack voltage issues, a self-circulating modulation (SCM) is proposed for the P²DAB converter. And by using the SOFC-parallel-SOEC-series architecture proposed in [10], the asymmetrical power characteristics of SOEC/SOFC do not degrade the efficiency of the P²DAB converter.

This paper is organized as follows. After this introduction, the topology and the basic phase shift modulation (PSM) of the P²DAB converter is reviewed. In section III, the SCM of the P²DAB converter and the SOFC-parallel-SOEC-series architecture are introduced for the interface of SOEC/SOFC to the grid. In section IV, the advantages and the drawbacks of the proposed interface system for SOEC/SOFC are discussed. Finally, in section V, the theoretical analysis of the SCM is verified on a 1MHz, 500W GaN-based P²DAB converter. Conclusions are made in section VI.

II. TOPOLOGY AND PHASE SHIFT OPERATION OF THE P²DAB CONVERTER

Fig.2 gives the topology of the P²DAB converter. By operating the m transformers in parallel on the low voltage side (LVs) and in series on the high voltage side (HVs),

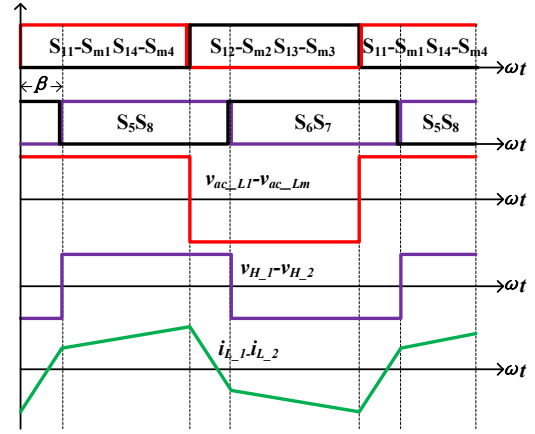


Fig. 3. Typical waveforms of the P²DAB converter with PSM

the P²DAB converter features high current-rating on the LVs and high voltage gain. The basic modulation strategy of the P²DAB converter is PSM, whose typical waveforms are given in Fig. 3. Phase shift β is added between the full-bridges on the LVs and the full-bridge on the HVs. Due to the series connection of the transformers on the HVs, the ac components of the currents $i_{L,1} \sim i_{L,m}$ are forced to be the same.

III. SELF-CIRCULATING MODULATION OF THE P²DAB CONVERTER AND THE SOFC-PARALLEL-SOEC-SERIES ARCHITECTURE

A. Self-Circulating Modulation of the P²DAB Converter

With PSM, every full bridges on the LVs of the P²DAB converter are transferring power. All of the transformers contributes to boosting voltage. This full-voltage-gain operation is suitable for interfacing the SOEC/SOFC system operating in SOFC mode at full power, at which the stack voltage is the lowest, as shown in Fig. 1. However, when the power is decreased in SOFC mode, the stack voltage increases. Since V_2 is clamped to be the grid voltage, it is thereby necessary to change the voltage gain of the P²DAB converter in order to keep the voltage-matching between the stack voltage and the referred grid voltage. Voltage-matching implies that V_1 and the referred V_2 are nearly the same. For DAB based converters, the optimal operating point occurs when voltage-matching is realized [15].

Therefore, the SCM is proposed for the P²DAB converter to change its voltage gain. Fig. 4 gives the typical waveforms of the P²DAB converter with SCM for a half of the full-voltage-gain. As shown, by disabling half of the m full-bridges on the LVs, the voltage-matching is maintained even when V_1 (stack voltage) doubles. This disabling is realized by keeping both low side switches in on-state. Since the currents $i_{L,1} \sim i_{L,m}$ are forced to be the same, there are circulating currents in the low side switches even though the full bridges they belong to are not transferring power. Therefore, additional conduction losses are generated.

Assume that n of the m full-bridges on the LVs are modulated in self-circulating, the remaining $m-n$ full-bridges are modulated to have the same phase shift to the full-bridge on the HVs. The sum of the voltage across the winding on the HVs of the transformer is the voltage across the switching node of the full bridge on the HVs as expressed in (1).

which happens in the SOEC mode, is actually the minimum. While all of the branches are enabled to deliver just half of the maximum power of SOEC/SOFC. Therefore, with the traditional interfacing architecture, it is very challenging in the design of a high efficiency P²DAB converter for the entire operating area.

Fig. 6 shows the SOFC-Parallel-SOEC-Series architecture proposed in [10]. With this new architecture, the power-handling problems mentioned in the last paragraph are solved.

For the SOFC mode, the configuration is the same as the traditional one shown in Fig. 5, where the stacks are connected to the P²DAB converter in parallel. At the highest power, the stack voltage is the lowest. All of the branches are enabled for the highest voltage gain and the strongest power flow capability. As the power decreases, more and more branches are disabled to keep the voltage-matching. And since the enabled branches still operates in high power, the zero voltage switching (ZVS) is guaranteed even though the converter itself is at low power.

For the SOEC mode, the configuration is different to the traditional one. The stacks are connected in series with the P²DAB converter, and then this series connection is connected in parallel to the grid. As a result, the I-V curve of the LVs of the P²DAB converter will have drooping characteristics as in the SOFC mode. Therefore, voltage-matching and ZVS can also be achieved at low power operating area of SOEC mode. Moreover, when V_{SOEC} is half of the grid voltage, the P²DAB converter have symmetrical power rating in both operation modes.

IV. ADVANTAGES AND DRAWBACKS OF THE PROPOSED INTERFACE SYSTEM FOR SOEC/SOFC

Comparison is made between the proposed interface system, which is the SOFC-Parallel-SOEC-Series architecture using the P²DAB converter with SCM, and the traditional architecture using the P²DAB converter with PSM.

The advantages of the proposed interface system include:

- Voltage-matching of the P²DAB converter is ensured for the entire operating area.
- Zero voltage switching of the P²DAB converter is guaranteed at low power.
- Switching losses in the disabled branches are zero.
- Symmetrical power rating of the P²DAB converter is achieved in both SOEC mode and SOFC mode.
- The power rating of the P²DAB converter is reduced.

The drawbacks of the proposed interface system include:

- Additional conduction losses are generated in the disabled branches.

V. EXPERIMENTS

In order to verify the proposed SCM for the P²DAB converter, a hardware prototype with two full-bridges on the LV side was built as will be described in this section. The implemented 400V/50V P²DAB converter is depicted in Fig. 7. The system is rated for 500W and exhibits a total volume of 378cm³ which corresponds to a power density of 1.3W/cm³.

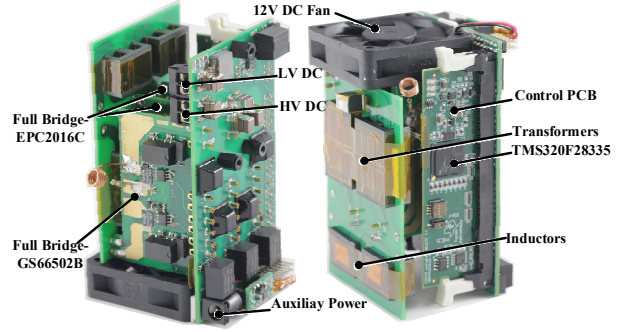


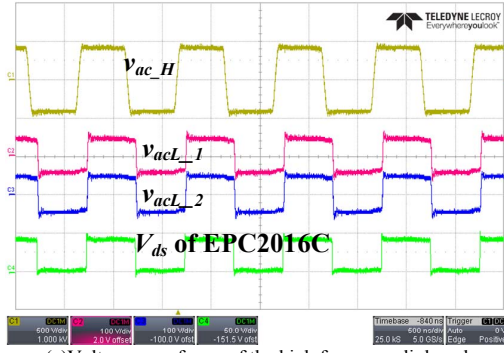
Fig. 7. Picture of the P²DAB hardware taken from different perspectives

TABLE I. TECHNICAL DETAILS OF THE P²DAB PROTOTYPE

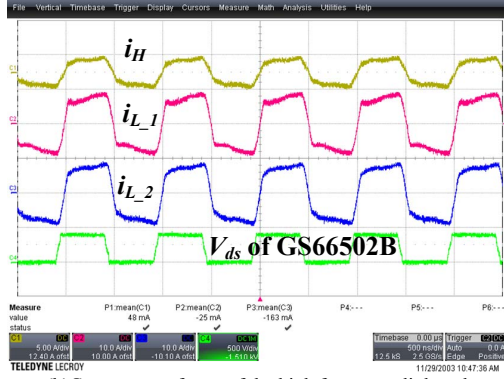
	Description	Parameter
Specifications of the prototype	Switching Frequency	1MHz
	DC voltage on the HV side	400Vdc
	DC voltage on the LV side	50Vdc
	Maximum power	530W
Power semiconductor	Switches on the HV side	GS66502B
	Switches on the LV side	EPC2016C
Transformer	Material for the core	ML91S
	Dimension of the core	2×EE-21.8-11.4-15.8
	Number of turns on the HV side	8
	Number of turns on the LV side	2
Inductor	Material for the core	ML91S
	Dimension of the core	1×EE-21.8-11.4-15.8
	Number of turns	1
DC capacitors	DC capacitor on the HV side	20×CKG57NX7T2J105M500JH
	DC capacitor on the LV side	63×C2220C105K1R1C7186
Cooling system	Fan	MC35357

As it can be seen from the picture, the converter is realized by means of six individual PCBs, which include three full-bridge PCBs equipped with GaN switches and their driving circuits, one digital control board based on TMS320F28335, one base-board equipped with power connectors and detecting circuits, and one PCB winding board. In order to extract losses from the power electronics, a 5cm×5cm×1cm 12V DC fan is mounted. No heat sink was attached to the PCBs, the heat generated in the semiconductors is spread by the PCB and quickly dissipated into the air with the help of the fan. Technical details of this prototype are given in Table I.

The waveforms of the P²DAB converter operating at 530W output power and 400V/50V rated voltage are shown in Fig. 8. The waveforms are labeled according to the circuit schematic shown in Fig. 2. As shown in Fig. 8, the waveforms have the same pattern as those in Fig. 3, except v_{ac_H} and v_{ds} of GS66502B, which ramp up/down too slowly. The ZVS of GS66502B is thereby not achieved. This slow switching is mainly due to the poor PCB layout.

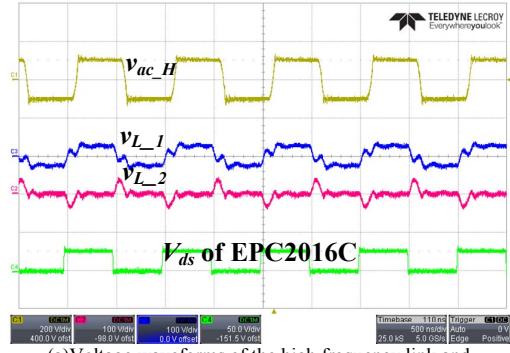


(a) Voltage waveforms of the high frequency link and the drain-source voltage of EPC2016C

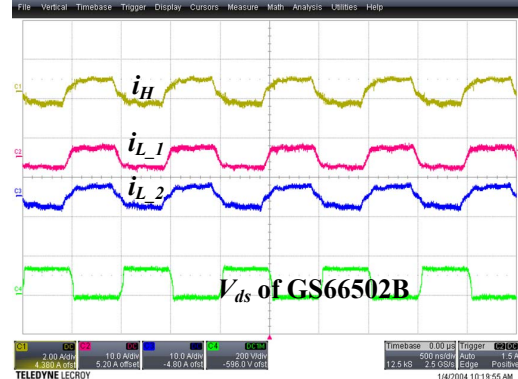


(b) Current waveforms of the high frequency link and the drain-source voltage of GS66502B

Fig. 8. Experimental waveforms of the P²DAB converter operating at 530W output power and 400V/50V rated voltage (Time: 500ns/div)



(a) Voltage waveforms of the high frequency link and the drain-source voltage of EPC2016C



(b) Current waveforms of the high frequency link and the drain-source voltage of GS66502B

Fig. 10. Waveforms of the P²DAB converter with SCM under half of the full voltage gain, 28V/100V (Time: 500ns/div)

9 and Fig. 10. The P²DAB converter is first operated with PSM in order to have the so-called full voltage gain. As shown in Fig. 9, with $V_1=14V$ as the input and $V_2=100V$ as the output, the prototype has a voltage gain around 7. And the voltage-matching is achieved as can be seen from the trapezoidal current waveforms.

The P²DAB converter is then operated with SCM in order to change the voltage gain. As shown in Fig. 10, with $V_1=28V$ as the input and $V_2=100V$ as the output, the voltage-matching is still kept by decreasing the voltage gain to around 3.5. Compared with the theoretical waveforms in Fig. 4, clearly visible is that the experimental waveforms in Fig. 10 show the same pattern. Therefore, the analysis of the SCM operation is verified. Compared with the measured current waveforms in full gain operation in Fig. 9(b), the measured current waveforms in half gain operation in Fig. 10(b) have more oscillations.

VI. CONCLUSIONS

In this paper, a self-circulating modulation (SCM) is proposed for the Partial Parallel Dual Active Bridge (P²DAB) converter. With the SCM, the voltage gain of the P²DAB converter can be adjusted to guarantee the voltage-matching under wide input/output voltage ranges. By using the P²DAB converter with SCM in a novel SOFC-Parallel-SOEC-Series architecture, challenges of designing interface system for SOEC/SOFC due to its current-dependent and low stack voltage and its asymmetrical power characteristic can be addressed. The SCM operation of the P²DAB converter is verified on a 1MHz, 500W, 400V/50V, GaN-based P²DAB converter.

The waveforms which show the variable voltage gain operation of the P²DAB converter with SCM are given in Fig.

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